

# DIMMING OF SUPERNOVAE AND GAMMA RAY BUSTS BY COMPTON SCATTERING AND ITS COSMOLOGICAL IMPLICATIONS

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## ABSTRACT

Free electrons deplete photons from type Ia supernovae through the (inverse) Compton scattering. This Compton dimming increases with redshift and reaches 0.004 mag at  $z = 1$  and 0.01 mag at  $z = 2$ . Although far from sufficient to invalidate the existence of dark energy, it can bias constraint on dark energy at a level non-negligible for future supernova surveys. This effect is correctable and should be incorporated in supernova analysis. The Compton dimming has similar impact on cosmology based on gamma ray bursts as standard candles.

*Subject headings:* cosmology: distance scale–theory

### 1. COMPTON DIMMING OF TYPE IA SUPERNOVAE

Type Ia supernovae (SNe Ia) are standardizable as *cosmological standard candles* to measure cosmological distance and thus infer the expansion history of the universe. Current observations on SNe Ia have enabled the discovery of the late time acceleration of the universe (Riess et al. 1998; Perlmutter et al. 1999). This discovery has profound impact on fundamental physics, leading to either a dominant dark energy component with equation of state  $w \equiv P/\rho < -1/3$  or significant deviations from general relativity at around Hubble scale. Ongoing and planned supernova surveys have the power to significantly improve these cosmological constraints and hopefully clarify the role of the cosmological constant in our universe (Albrecht et al. 2006).

Various astrophysical processes, besides the possible intrinsic evolution in SN luminosity, can degrade the standard candle merit of SNe Ia by altering the supernova flux. An incomplete list include gravitational lensing magnification (Holz 1998), peculiar velocity (Hui & Greene 2006), dust extinction and incomplete K-correction. If not handled correctly, they can not only increase statistical errors, but also systematically bias the cosmological constraints. In this paper, we point out a new source of systematical errors, relevant for precision cosmology.

The universe is (almost) completely ionized after  $z = 6$ . Free electrons in the universe treat all low energy photons ( $h\nu \ll m_e c^2$ ) equally and Compton scatter<sup>1</sup> off them with equal probability  $\exp(-\tau)$ , where  $\tau$  is the Thomson optical depth

$$\tau(z) = \int_0^z \sigma_T n_e^{free}(z) \frac{acd z}{H(z)} = \int_0^z \sigma_T n_e(0) X_e(z) \frac{(1+z)^2}{H(z)} dz. \quad (1)$$

Here,  $\sigma_T$  is the Thomson cross section,  $n_e^{free}(z)$  is the number density of free electrons and  $X_e(z)$  is the ioniza-

tion fraction.  $X_e(z) \simeq 1$  at  $z < 6$ .  $H(z)$  is the Hubble constant and  $a = 1/(1+z)$  is the scale factor. There are two competing effects on the flux of a given celestial object. (A) For photons originally emitted towards us, on the average  $1 - \exp(-\tau) \simeq \tau$  of them are Compton scattered away and escape of observation. (B) Photons otherwise can not reach us may be scattered toward us. If the celestial object is non-evolving and the universe is static, these two effects cancel each other exactly and the flux is unchanged.<sup>2</sup> This can be proved straightforwardly by the aid of photon number conservation. However, none of the conditions is realistic. First of all, our universe is expanding. Scattered photons take longer time to reach us and thus suffer more energy loss. More importantly, SNe Ia only last for months, much shorter than the time it takes for photons to reach us. Scattered photons travel extra distance and take extra time to reach us. As a consequence, only those photons originally emitted within a solid angle  $\Omega_{scatter} \sim ct/D$  toward us can be scattered while reach us during the event period. Here,  $t$  and  $D$  are the life time and the distance of SNe Ia, respectively. For SNe Ia,  $\Omega_{scatter}/4\pi \sim 10^{-11} \ll 1$ . Thus it is virtually exact that no scattered photons can reach us. Since effect B vanishes, for SNe Ia, Compton scattering alters the flux  $F$  to  $F \exp(-\tau)$ . We call it the Compton dimming. Its amplitude is

$$\frac{\delta F}{F} = -2 \frac{\delta D_L}{D_L} = \exp(-\tau) - 1 \simeq -\tau. \quad (2)$$

Here  $D_L$  is the luminosity distance. This results in a systematic shift in the distance moduli  $\mu$ ,

$$\Delta\mu = 5 \log_{10}(1 + \delta D_L/D_L) \simeq 1.086\tau. \quad (3)$$

$\tau$  increases quickly with redshifts, scales as  $(1+z)^3 - 1$  at low redshift and  $(1+z)^{3/2}$  at high redshift until the epoch of reionization. We adopt the WMAP cosmology with  $\Omega_m = 0.26$ ,  $\Omega_\Lambda = 1 - \Omega_m$  and  $\Omega_b h = 0.032$  (Spergel et al. 2007) for the numerical evaluation. Compton scattering dims the supernova flux by 0.004

<sup>1</sup> Free electrons have thermal and kinetic motions. So what happened actually is the inverse Compton scattering. Inverse Compton scattering results in photon energy change at a level of  $10^{-3}$  ( $k_B T_e/m_e c^2$ ,  $v/c \sim 10^{-3}$ ). For CMB photons, this process results in the well known Sunyaev-Zel'dovich effect. However, this photon energy change is irrelevant for this paper since none of scattered supernova photons reach us in time.

<sup>2</sup> Tiny energy change in scattered photons is neglected in this statement.

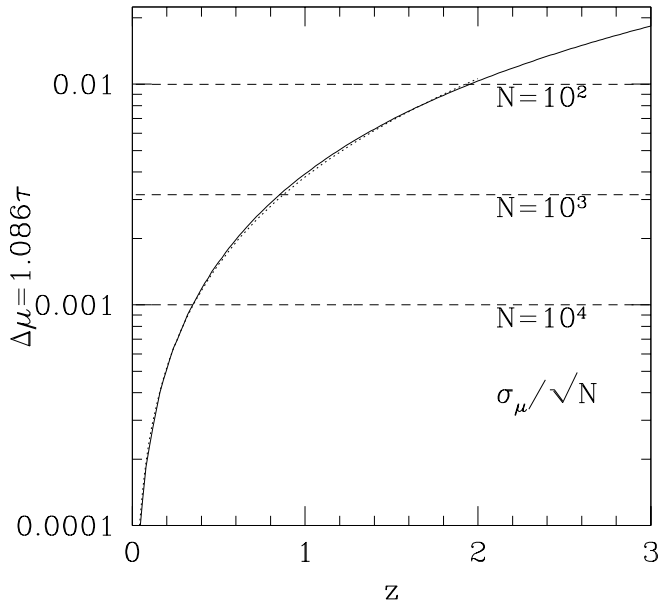


FIG. 1.— Systematic shift in the distance moduli  $\mu$  caused by Compton scattering (solid line). Although the dimming is only 0.4% in flux at  $z = 1$  and 1% at  $z = 2$ , the systematical errors induced are comparable to statistical errors induced by intrinsic dispersion in SN fluxes for future SN surveys with  $\sim 1000$  SNe Ia at  $z > 1$ . Here intrinsic dispersion  $\sigma_\mu = 0.1$  mag is adopted and the associated statistical errors are shown as dash lines. The function form  $\mu^L z + \mu^Q z^2$  adopted to handle possible unknown systematic errors is an excellent parametrization for this type of  $\Delta\mu$  at  $z \leq 2$ , which is shown as the dot line, almost indistinguishable from the real  $\Delta\mu$ .

mag at  $z = 1$  and 0.01 mag at  $z = 2$  (Fig. 1). This dimming is far from sufficient to challenge the existence of dark energy. Nonetheless, its impact is non-negligible for precision cosmology based on supernovae. Future SN surveys such as JDEM, will measure  $\sim 1000$  SNe Ia at  $z > 1$ . For these surveys, the major statistical uncertainty is the SN intrinsic fluctuations. With  $N \sim 1000$  SNe, intrinsic fluctuations are reduced to a level of  $\sigma_\mu/\sqrt{N} \simeq 0.003$  mag. Here  $\sigma_\mu$  is the intrinsic dispersion in SN luminosities. So the Compton dimming must be corrected, otherwise the induced systematical errors would be comparable to the statistical errors. LSST can measure  $\sim 10^5$  SNe Ia to  $z \sim 1$ . For it, there are extra errors associated with photo- $z$  uncertainties, whose dispersion is  $\sim 0.01$ - $0.1$ . Even so, for LSST, systematical error induced by Compton scattering likely overwhelms the statistical errors induced by intrinsic fluctuations and photo- $z$  uncertainties.

Since the Compton dimming increases toward high redshift, it biases  $w$  toward more negative value at higher redshift (Fig. 2). We isolate the impact on  $w$  by fixing other cosmological parameters at their fiducial values and show the result in Fig. 2. The systematic shift  $\Delta w \sim -2\tau$  (roughly 4 times the fractional error in the distance). It shifts  $w$  by  $-0.008$  for SNe Ia at  $z = 1$  and by  $-0.017$  for SNe Ia at  $z = 1.7$ . This systematic bias is comparable to the rms uncertainty in the pivot  $w$  for stage IV SN surveys (Albrecht et al. 2006). Thus it is

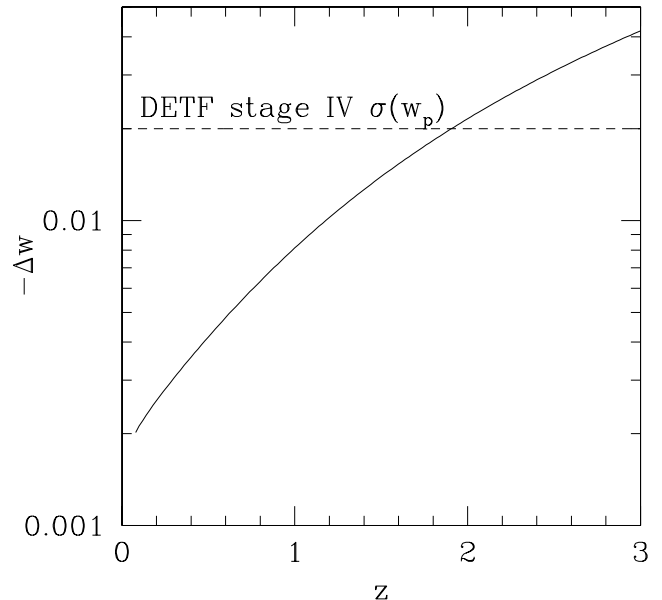


FIG. 2.— Bias in  $w$  induced by the Compton dimming (solid line). In this estimation, other cosmological parameters are fixed at their fiducial values in order to isolate the impact on  $w$ . Roughly  $\Delta w \sim -2\Delta\mu \simeq -2\tau$ . The dash line is the rms uncertainty in  $w = w_p$  at the pivot  $a = a_p$  for the stage IV supernova surveys (Albrecht et al. 2006).

of particular importance for the key dark energy task, to confirm or invalidate the existence of the cosmological constant.

Clearly we must take this effect into the analysis of these future surveys in order not to bias the cosmological constraints. Observationally, this effect can not be corrected, since it lacks observational consequences such as reddening that can be applied to separate from other effects. Can commonly adopted parametrization of systematic uncertainties such as the intrinsic evolution well incorporate this effect? The answer is yes. It can be fitted with excellent accuracy by  $\Delta\mu = \mu^L z + \mu^Q z^2$  with  $\mu^L = 2.3 \times 10^{-3}$  and  $\mu^Q = 1.5 \times 10^{-3}$  (Fig. 1). On one hand, this means that, the Compton dimming is automatically corrected through this kind of self calibration. On the other hand, this implies that, without knowledge of the Compton dimming, it could be misinterpreted as an intrinsic evolution in supernova luminosity.

Fortunately, this effect is straightforward to take into account from the theory part. Besides the cosmological parameter  $\Omega_m$ , the dark energy density  $\Omega_{DE}$  and equation of state  $w$  that supernova cosmology aims to constrain, only an extra input of  $\Omega_b h$  ( $\tau \propto \Omega_b h$ ) is required to predict  $\tau$ . Furthermore, we do not need the exact number of  $\Omega_b h$  to perform this correction. 10% accuracy in  $\Omega_b h$  is sufficient to render this source of error negligible for any foreseeable surveys. Current constraint from CMB already reaches this accuracy. So, the Compton dimming is completely correctable.

So far we have implicitly neglected fluctuations in  $\tau$  along different lines of sight, so  $\tau$  calculated above is actually the ensemble average  $\langle \tau \rangle$ . In reality, there are

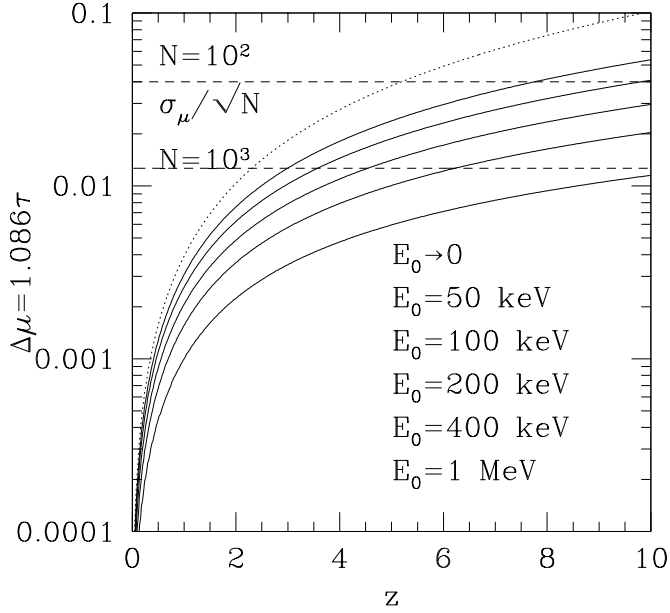


FIG. 3.— The systematic shift in the distance moduli  $\Delta\mu$  for GRBs, assuming the universe is completely ionized at  $z \leq 10$ . Since  $\gamma$ -ray photons are energetic, the Compton scattering cross section is now energy dependent. This causes  $\Delta\mu$  and  $\tau$  to decrease with photon energy. Here,  $E_0$  is the redshifted  $\gamma$ -ray photon energy. The dash lines are the statistical errors for 100 and 1000 GRBs, respectively.  $\sigma_\mu = 0.4$  mag is adopted for GRBs.

fluctuations in  $\tau$  along different lines of sight. For SNe Ia, which are observed at  $z \lesssim 2$ , the ionization fraction  $X_e(z) = 1$  is an excellent approximation. Fluctuations in  $\tau$  are thus mainly caused by fluctuations in the electron number density. It is straightforward to show that  $\sigma_\tau/\langle\tau\rangle \ll 1$ , where  $\sigma_\tau$  is the rms fluctuation in  $\tau$ . Since the Compton dimming is already a small effect, tiny fluctuations above its mean do not cause any observable effect and can thus be safely neglected.

## 2. COMPTON DIMMING OF GAMMA RAY BURSTS

Gamma ray bursts (GRB) are likely standardizable and can serve as cosmological standard candles (Xu et al. (2005) and references therein). They have the merit to be sufficiently bright to be observed at redshift  $z > 6$  and thus provide important cosmological constraints complementary to SNe Ia.

GRBs suffer similar Compton dimming. But since the  $\gamma$  photon energy is now comparable to the electron mass,

the cross section of the Compton scattering is suppressed and becomes energy dependent.  $\sigma_T$  in Eq. 1 should be replaced by  $\sigma(E_0(1+z)/m_e c^2)$ , which is given by the Klein-Nishina formula  $\sigma(x) = \frac{3}{4}\sigma_T\{(1+x)[2x(1+x)/(1+2x) - \ln(1+2x)]/x^3 + \ln(1+2x)/(2x) - (1+3x)/(1+2x)^2\}$  (Rybicki & Lightman 1976). Here  $E_0$  is the observed redshifted energy of  $\gamma$ -ray photons.  $\tau$  and  $\Delta\mu$  are now energy (frequency) dependent. The Compton dimming decreases with the photon energy (Fig. 3). Despite the suppression in cross section, the Compton dimming can still reach  $\sim 0.01$ - $0.05$  mag, because GRBs often reside at high redshifts. GRBs have larger intrinsic fluctuations than SNe Ia. However, if more than a hundred high redshift GRBs are observed and applied to constrain cosmology, this Compton dimming may become non-negligible.

Similar to the case of SNe Ia, it is straightforward to correct this Compton dimming effect for GRBs at  $z < 6$ . However, correcting it for GRBs at  $z > 6$  is subtle. For example, patchy reionization can cause order of unity fluctuations in  $\tau$  along different lines of sight, as suggested in radiative transfer simulations (Holder et al. 2007). This could forbid complete correction of Compton dimming from the theory part, even if the average reionization fraction  $X_e(z)$  at  $z > 6$  is perfectly known. Since the reionization history is poorly understood, we are not able to estimate to what level the Compton dimming can be corrected for these high redshift GRBs. A possibility is to rely on other surveys to measure  $\tau$  along each line of sight and to correct for the Compton dimming. For example, future 21-cm surveys of the reionization epoch can be applied to reconstruct the optical depth along each line of sight, through tight correlation between the optical depth and the 21-cm brightness temperature (Holder et al. 2007).

## 3. SUMMARY

We point out that Compton scattering dims supernova flux at a level non-negligible for future supernova cosmology and must be taken into the analysis. It also has similar impact on cosmology based on GRBs.

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